Analysis of a novel laser welding strategy for electrical steel laminations

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***Abstract*— The magnetic core of rotating electrical machines is usually constructed of stacked and fixed non-oriented electrical steel laminations. The process of stacking and fixing has a detrimental effect on the magnetic properties. Two main factors are the cause of the magnetic deterioration, namely the induced mechanical stress as well as increasing eddy currents due to a damage of the insulation layer between the sheets. As a result magnetic loss increases and permeability decreases. The presented novel welding strategy shows promising results to decrease the magnetic deterioration, especially as an approach for higher frequency applications**

Besides interlocking, linear welding is a common technique to join laminations to a package. The target of the fixation is to fulfill requirements of mechanical strength and torsional rigidity even at high speed of a rotor. However, the magnetic property change cannot be neglected. Electrical steel sheets are usually characterized in standardized tests of the steel sheets prior to the further manufacturing process. Machine design and machine simulation use this early data to estimate loss and magnetic behavior of electrical machines. The manufacturing processes is disregarded and actual machine behavior can significantly differ from the estimations. In order to improve understanding of the welding influence and study possibilities to limit its effect, this paper studies the effect of different welding approaches.

Ring cores are stacked from 0.5-mm sheets of insulated industrial steel with a silicon content of 2.4 wt.%. The stacks are joined by laser welding at atmospheric pressure and under vacuum. Statistical distribution of single welding spots are studied alongside common linear welding lines across the entire height of the stack. The aim is to minimize the alteration of magnetic behavior while maintaining full load capacity. Magnetic ring core measurements are supplemented by microstructural analysis in order to determine the directly affected regions of the welding process. Differences of total loss, frequency behavior and magnetization characteristics are analyzed.

Keywords— magnetic hysteresis, packaging of electrical steel sheets, magnetic loss, eddy currents, manufacturing process, material degradation, electrical machines

I. Introduction

The magnetic properties of the magnetic core of an electrical machine is determinative for the attainable efficiency and power density of the final machine. The magnetic flux density in the airgap is directly proportional to the generated torque. Easy magnetization and low loss up to high frequencies are target values for the soft magnetic material. Increasing motor speeds however, lead to higher requirements for the mechanical strength and rigidity of the manufactured core and thereby, are further, challenging specifications for the material. Thus, not only magnetic properties, but also mechanical behavior is of interest considering the material in the final application.

Measures to improve the magnetic behavior of the material are exerted during material production, mainly a defined alloying concept with silicon content of maximum 3.0 wt.% Si, fabrication of thin sheet to reduce eddy current loss and controlling of microstructure and texture to improve magnetization and minimize loss [1-2]. However, a consideration of only material production measures is not sufficient, because the processing and manufacturing of the magnetic core alters the magnetic properties significantly [3-4]. Cutting, stacking and fixing induces mechanical stress to the material, which severely deteriorates the magnetic properties [5-6]. Thus, the processing of the material needs to be incorporated in the considerations of material application.

Welding lines in axial direction of the laminations, as depicted in Fig. 1 (a) are commonly used to connect individual laminations of electrical steel into a rotor or stator [4-5]. The connection is obtained by local melting and solidifying of the material. The welding leads to a solid joint that fulfills requirements on strength and geometry. The magnetic property deterioration is caused mainly by three factors, the formation of short circuits along the welding connection, a local change of microstructure in the melted and heat affected zone (HAZ) and induced mechanical stress due to the thermal impact. Local short circuits are formed by connection of the lamination and destruction of the insulating layer which normally separates the steel laminations [7]. The melting also leads to a primary solidification of the material in the welding joint as well as possible grain growth. The HAZ can reach several millimeters into the material [8]. Residual stress remains in the material after welding. In general, the effect of mechanical stress on the magnetic properties is detrimental [9, 10].

Variations in the welding process are obtained by variation of welding parameters, i.e., heat input, energy, and welding speed.

In this study, however, a novel welding strategy is presented. The idea is to limit magnetic deterioration through the use of welding spots instead of welding lines. A statistical distribution and a spiral positioning of welding spots is compared to common orientation of welding lines on the outer side of the ring cores. The aim of this study is to determine the effect of different welding strategies on the magnetic properties at different frequencies and excitations and correlations of results with phenomenological changes in the welding seam and HAZ.

II. Experimental Study

A. Material and Geometry

The material which is used in this study is a fully-finished 0.5-mm, 2.4 wt.% Si FeSi electrical steel. Ring laminations with an inner diameter of 48 mm and an outer diameter of 60 mm were fabricated by spark erosion. The ring cores are stacked from 10 laminations each and were welded with the following strategies.

B. Welding

All welding trials were carried out with a Trumpf TruDisk 16002 Disk Laser which has a maximum power of 16 kW and a minimal fiber diameter of 200 µm. The power can be decreased to 2 % (320 W) of the maximum power. A Precitec YW-30 with an aspect ratio of 2:1 was utilized as focusing optics. Therefore, the focal diameter was 400 µm for each trial. In each case, 10 electrical ring laminations are joined to one ring core. Different laser process modifications are applied on the welding trials. The reference process is linear laser beam welding with no further alterations such as shielding gas or vacuum. For the ring cores with linear welding lines, two lines for one ring core and four lines for the other ring core, evenly spaced around the circumference, are used to join laminations.

To minimize short circuits between the sheets, a new strategy, laser spot welding, is introduced. The first laser spot joins the first three ring laminations, the next one joins the next three laminations, starting with the second ring. By this method, each spot is connected to the prior spot by two rings, Fig. 1 ($c_{1,2}$). Two different patterns are used for this laser process modification. In the first, the spots were placed in uniform distances of 10° within a section of 90°. This pattern was repeated four times around the circumference, so that a spirally oriented pattern resulted. For the second pattern, there was a statistical distance between the different spots.

Both test series, the linear weld and the different patterns of the spot weld, are also conducted with laser beam welding under vacuum. The experiments are carried out at a pressure of 1 mbar. All welding patterns are depicted in Fig. 1 and TABLE 1.

C. *Magnetic charactrerization*

Magnetic characterization is performed on a Brockhausen measurement system with a ring core tester. The welded ring cores are equipped with isolation foil and both 80 windings for the primary and secondary induction coils. The samples are characterized at 50 Hz, 400 Hz, 750 Hz and 1000 Hz for polarizations between 0.1 to 1.5 T.

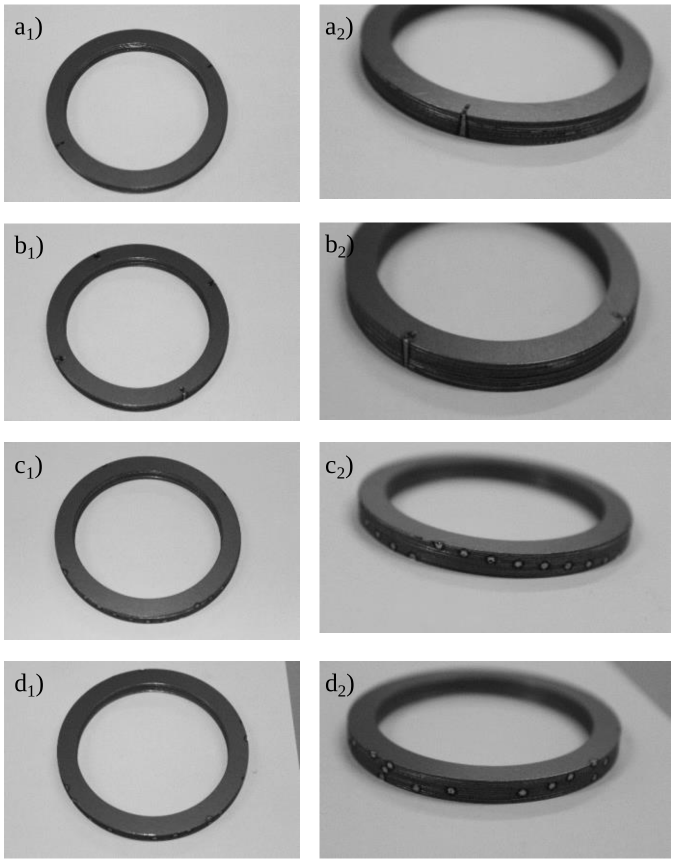


Fig. 1: Distribution of welding joints for different laser process modifications. Top view $_1$, cross section $_2$ (a) Ring core 1, two linear welding lines, (b) Ring core 2, four linear welding lines, (c) Ring core 3, spirally oriented welding spots, (d) Ring core 4, statistical distribution of welding spots.

TABLE I. Specifications of ring core samples

	description	*welding pressure*	*image*
Ring core 1	two linear welding lines	atmosphere and 1 mbar	Fig.1 (a)
Ring core 2	four linear welding lines	atmosphere and 1 mbar	Fig.1 (b)
Ring core 3	spirally oriented welding spots	atmosphere and 1 mbar	Fig.1 (c)
Ring core 4	statistical distribution of welding spots	atmosphere and 1 mbar, 100 mbar	Fig.1 (d)

III. Results and Discussion

A. Impact of welding on the microstructure

Process parameters for the reference linear Laser welding at atmospheric pressure without any modifications were determined throughout welding trials. In this process, it was crucial to apply laser power ramps. This is on the one hand to avoid spatters due to the sudden keyhole development and on the other hand crater formation at the end of the weld. The welding velocity was 2.2 m/min at a power of 480 W.

As it can be seen in Fig. 2 (a), the grain structure was significantly changed in the weld seam itself. Furthermore, the grain growth did not stop at the fusion line, but the fusion line itself can be found within the grains. No significant change in the grain size can be seen in the HAZ, thus a possible beneficial impact on the magnetizability due to grain growth should be comparatively low. The weld seam itself is rather unusual for a laser weld, as it is 0.95 mm in width while only 0.66 mm depth. The weld seams measured area is 0.36 mm².

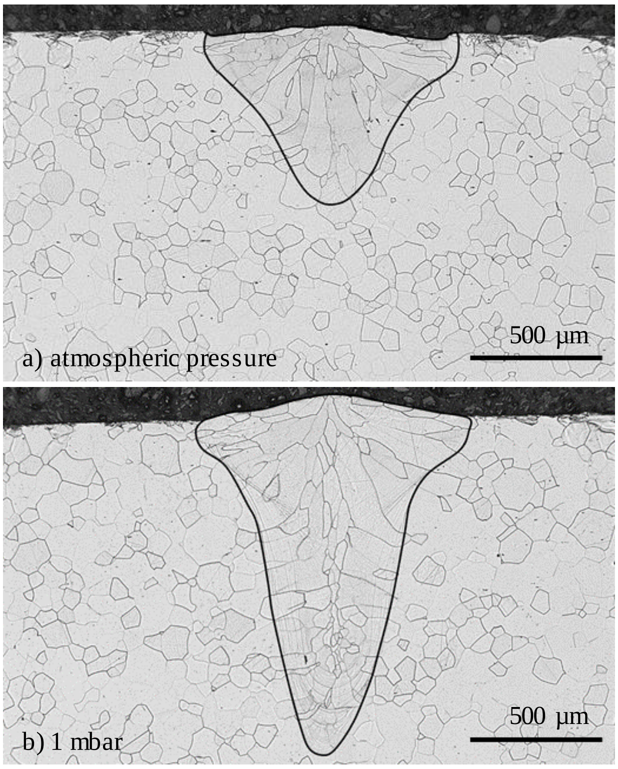


Fig. 2: Cross sections with marked fusion line for linear laser weld (a) at atmospheric pressure, (b) at a pressure of 1 mbar.

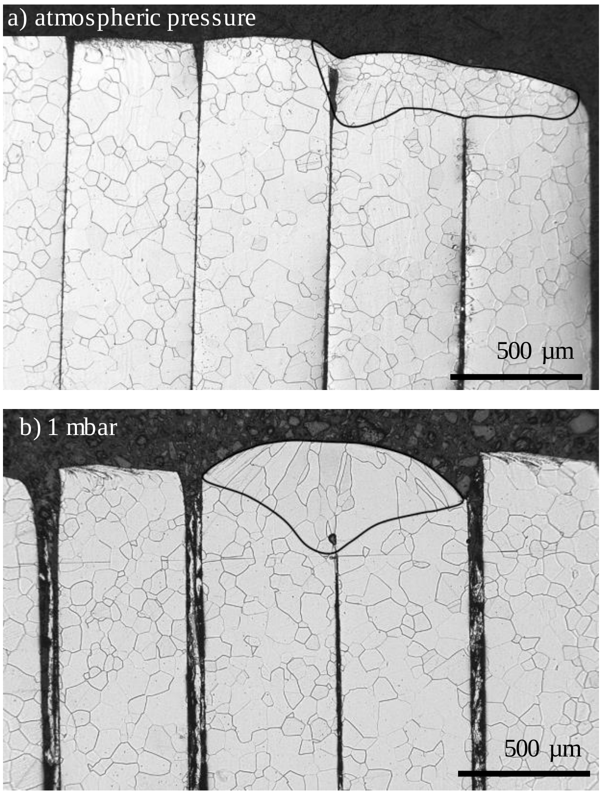


Fig. 3: Cross sections with marked fusion line for laserspot weld (a) at atmospheric pressure, (b) at a pressure of 1 mbar.

In Fig. 2 (b) results of the linear laser beam welding at a pressure of 1 mbar are depicted. Due to the reduced pressure, the penetration depth is significantly increased when the welding parameters are kept constantly. The weld in depth is 1.3 mm, while the width is unchanged compared to the value of 1 mm of the laser weld at atmospheric pressure. The weld seams measured area is 0.67 mm, nearly double the area of the atmospheric pressure weld seam. The grain size is comparable to the reference weld. A difference can be found in the lower center line of the weld, where smaller grains than those in the base material can be found.

For the laser spot welding at atmospheric pressure the spot welds size is 1 mm in width and 0.29 mm in depth. The measured area is 0.18 mm², Fig. 3 (a). The challenge for this process was to achieve a spot weld without defects such as cavities or blowholes. Due to the low depth and in comparison much higher width of the spot combined with the welding time of only 110 ms, the grains are smaller than in the base material.

The last process modification is the laser spot welding at a pressure of 1 mbar. Although the laser power was reduced while the welding time was the same as in the spot welding trials at atmospheric pressure, the penetration depth is increased by 33 %. The weld seam width is 1 mm and only two sheet rings were joined instead of three. The measured area of the weld seam is 0.25 mm², Fig. 3 (b).

B. Influence on J-H-characteristics

The welding of laminations of a ring core also has a significant effect on the magnetic properties of the lamination stack. The results show that the different strategies affect the properties distinctly. In Fig. 4 the *J*-*H*-hysteresis curves at three polarizations at 50 Hz are displayed. Remanence J_r, permeability μ, coercivity H_c and required magnetization H_{max} to reach a fixed polarization changes for the different ring cores at all polarization levels.

The samples can be characterized by the two general laser welding approaches. Ring cores 1 and 2 connect the laminations with linear welding lines and ring cores 3 and 4 connect the laminations with local welding spots. In Fig. 4 (a) the *J*-*H*-hysteresis curves at 50 Hz and 0.5 T are depicted. It is evident that ring cores 1 and 2 have overall better magnetic properties when compared with ring cores 3 and 4. The coercivity is smaller, thus indicating smaller magnetic loss, because the width of the hysteresis curve affects the hysteresis loop area i.e., the magnetic loss.

The required magnetization to reach 0.5 T is smaller for the samples with linear welding. Two welding lines are evidently preferable to four welding lines, because the magnetically affected volume due to residual stress, microstructure change and eddy current paths is obviously smaller. However, as stated in the introduction, the mechanical strength and torsional rigidity of a construction is also important for the application. Thus the number of welding lines on a geometry has to meet the requirements of both magnetic and mechanical performance. In this paper, the magnetic properties are analyzed to compare the welding strategies. The aim is to identify the potential of the novel welding strategy and study the effect on magnetic properties in detail.

For higher polarization, i.e., 1.0 T (Fig. 4 (b)) and 1.3 T (Fig. 4 (c)) the observed tendencies are similar. The effect on coercivity decreases with polarization as depicted in TABLE II. Here, the relative change of coercivity compared to ring core 1 for each polarization level is displayed. The relative increase of ring core 4 decreases from 27% to 22%. For ring core 2 it decreases from 6% to 4%. So, the deterioration of magnetic properties is most pronounced at low polarizations.

Though, the magnetic properties at 50 Hz indicate that the linear welding is beneficial, a comprehensive characterization requires the consideration of frequency, because the eddy current loss is of minor impact at low frequencies but becomes dominant at high frequencies.

TABLE II. COERCIVITY AND RELATIVE INCREASE AT 50 HZ AND DIFFERENT POLARIZATION LEVELS

	0.5 T	***1.0 T***	***1.3 T***
Ring core 1	46 A/m	68 A/m	77 A/m
Ring core 2	49 A/m (+6%)	71 A/m (+5%)	81 A/m (+4%)
Ring core 3	57 A/m (+23%)	82 A/m (+21%)	92 A/m (+19%)
Ring core 4	59 A/m (+27%)	84 A/m (+25%)	94 A/m (+22%)

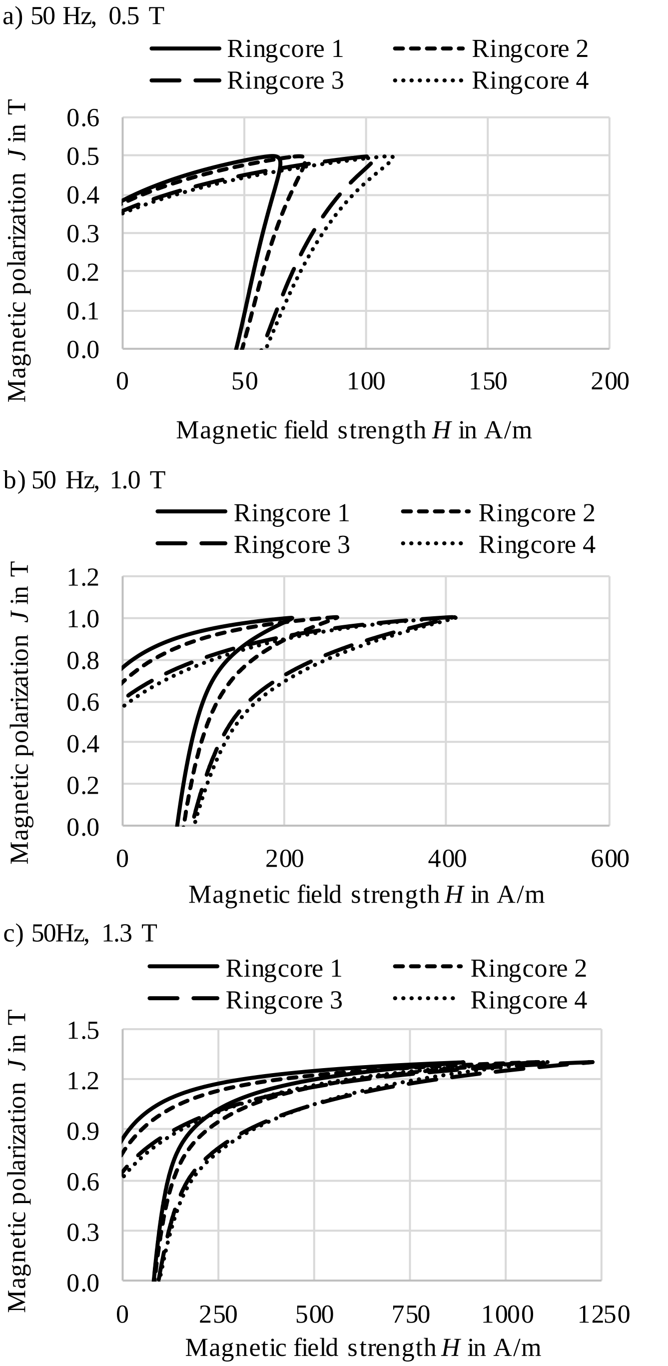


Fig. 4: *J*-*H*-hysteresis curves at 50 Hz for Ring cores 1-4 at three polarizations, (a) 0.5 T, (b) 1.0 T and (c) 1.3 T.

C. *Influence of frequency*

The influence of frequency on the magnetic properties of the welded ring cores has to be included in this study, because the underlying effects of welding on the magnetic properties have distinctive frequency dependencies. In this context, the effect on total magnetic loss at different frequencies can give an indication of the different influences. In classical loss theory the total magnetic loss can be divided into three parts (1), the hysteresis loss P_{hyst}, classical eddy-current loss P_{class} and the excess loss P_{exc} [11, 12].

$$P_s = P_{hyst} + P_{class} + P_{exc} \quad (1)$$

These components each have a different frequency dependence (2) with eddy current loss being the most affected with approximately quadratic increase with frequency [11, 12]. In this equation f is the frequency and $\hat{B}$ the peak induction.

$$P_s = k_{hyst} \cdot \hat{B}^2 \cdot f + k_{cl} \cdot \hat{B}^2 \cdot f^2 + k_{exc} \cdot \hat{B}^{1.5} \cdot f^{1.5} \quad (2)$$

Magnetic loss is affected by material parameters, e.g., microstructure, mechanical stress or lamination thickness [2, 10-13]. Mechanical stress as well as grain size influence P_{hyst} [10, 13-15], whereas the welding joint between the laminations can affect the classical eddy current term, because this term depends on sheet thickness d_{sheet} (3), which effectively is increased locally depending on the number of sheets which are sectionally connected.

$$P_{cl} = \frac{(\pi \cdot f \cdot d_{sheet} \cdot \hat{B})^2}{6 \cdot \rho \cdot \rho_{el}} \quad (3)$$

In Fig. 3 the magnetic loss at 50 Hz and 1000 Hz is depicted for two polarizations, 1.0 T (Fig. 5 (a)) and 1.3 T (Fig. 5 (b)). At 1.0 T and 50 Hz ring core 1 has the lowest total loss with 1.6 W/kg. Ring core 2 with four linear welding lines has slightly higher loss with 1.7 W/kg. Both, ring core 3 and 4 have higher loss with 1.9 W/kg. At 1000 Hz, i.e., twentyfold frequency, the loss for each ring core increases more than 100 times. For ring core 4 the relative increase is smallest compared with the other ring cores. Both, ring core 1 and 2 have a higher relative increase than ring core 3 and 4. At 1.3 the tendencies are analogous but with a larger relative increase for all ring cores.

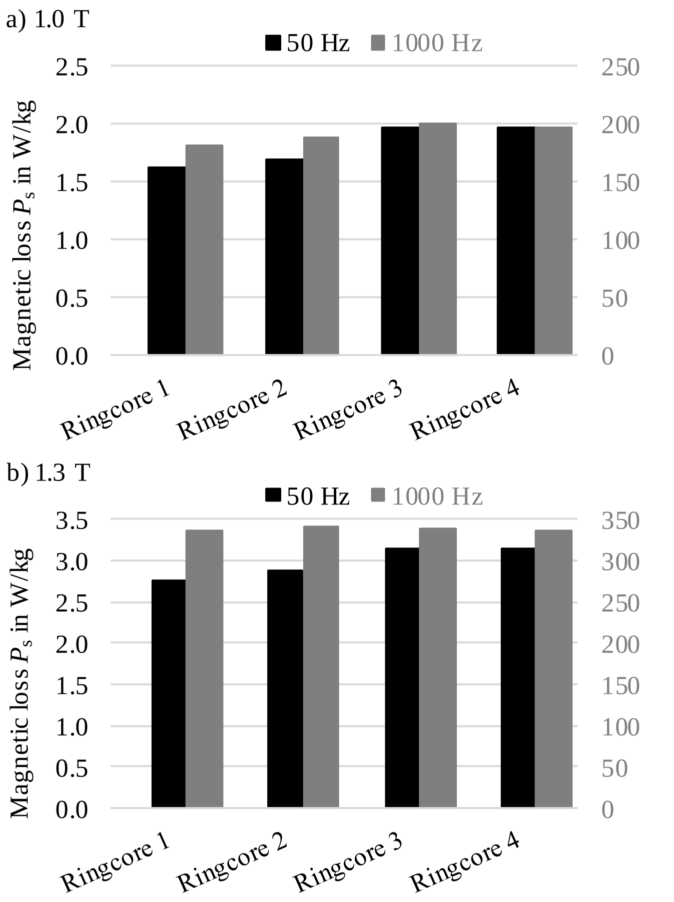


Fig. 5: Magnetic loss P_S at 50 Hz and 1000 Hz and different polarizations, (a) 1.0 T, (b) 1.3 T.

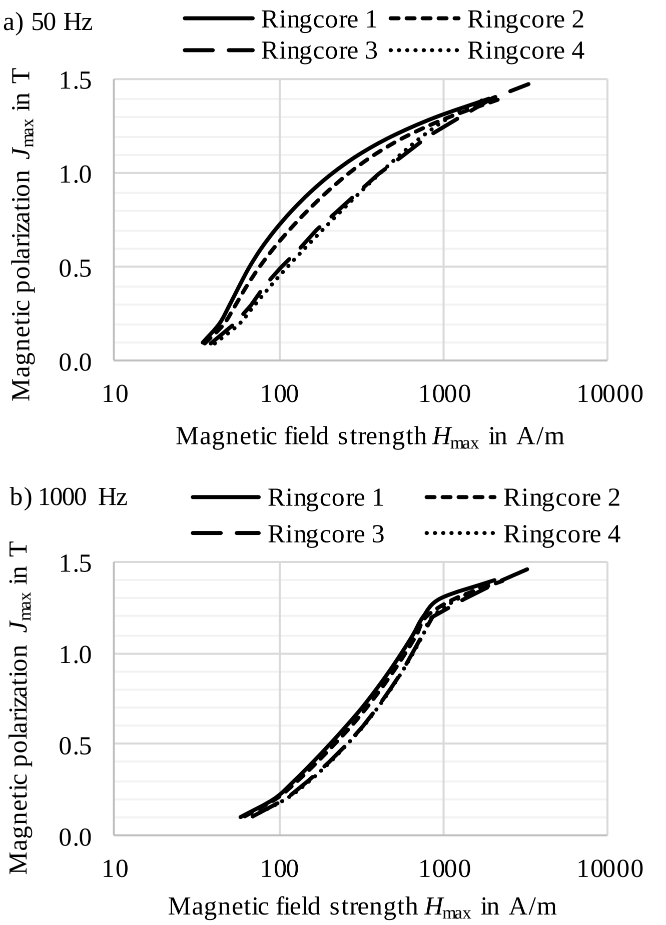


Fig. 6: Magnetization curves of Ring cores 1-4 at different frequencies, (a) 50 Hz, (b) 1000 Hz.

The results indicate that dynamic loss components, i.e., eddy current loss and excess loss are larger in ring cores 1 and 2, because they have a stronger relative loss increase with frequency. A possible explanation is that the eddy currents are larger because more laminations are connected to each other. In ring cores 3 and 4 laminations are connected by separate welding spots, i.e., more additional eddy currents but a smaller individual size. However, the contribution of excess loss needs to be studied in greater detail. The overall better loss properties of ring cores 1 and 2, especially at medium polarizations and low frequencies can be connected to lower residual stress and change in microstructure, which affect the hysteresis term of the total loss. In order to improve the novel welding strategy with welding spots, the focus should be placed on a reduction of residual stress of the ring cores or control of microstructure change. The effect of microstructure can be further studied with microstructural analysis and variation of atmosphere pressure, as in section *D*.

Besides the effect on magnetic loss, frequency also affects the magnetization behavior. In Fig. 6 magnetization curves at 50 Hz and 1000 Hz are displayed. At 50 Hz magnetization for Ring core 1 is easiest for the entire polarization range. Ring core 2 with the double amount of linear welding lines has a slightly inferior magnetization. These changes are however slight when compared with the ring cores with welding spots. The magnetization curves for ring core 3 and 4 are very similar. In comparison with Ring cores 1 and 2 the magnetization curves are flatter. This could be a further indication of increased residual stress, because strain leads to a flattening of the magnetization curve [10, 12-15].

At higher frequencies the magnetization behavior deteriorates for small and especially for medium polarizations. However, the difference between the individual ring cores is less distinct, so that at high frequencies the magnetization of ring cores 1 and 2 is only slightly better compared to ring cores 3 and 4.

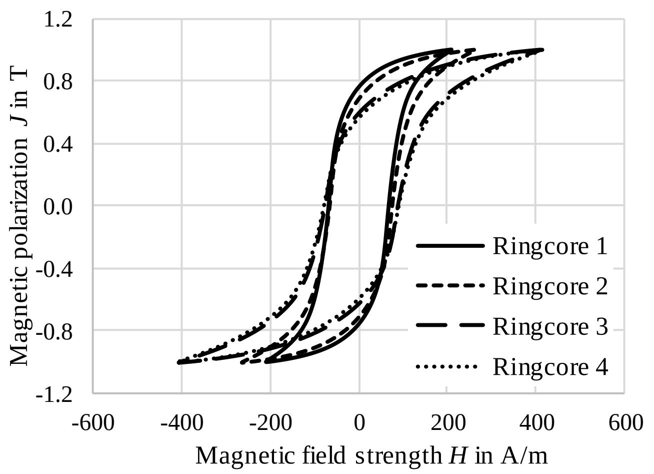
D. Impact of atmospheric pressure and vacuum

Besides the welding at atmospheric pressure, welding under vacuum was studied. The results are depicted in Fig. 7 and Fig. 8. Welding condition has an effect on the magnetic properties. At 50 Hz and 1.0 T properties for samples welded under vacuum are slightly inferior to the samples welded under atmospheric pressure for ring cores 1 and 2. They deteriorate to some extent. Ring cores 3 and 4 improve slightly so that the hysteresis loops are more uniform for the vacuum welded ring cores.

In section *A* possible explanations for the difference are discussed The microstructural analysis shows differences for the grain structure in the welding seam, size of the HAZ, penetration depth and size of the welding spots. Generally, under reduced pressure, i.e., 1 mbar, the microstructure change spreads deeper into the material so that a larger proportion of the material is affected. The linear laser beam welded samples also show a stronger deterioration at 1 mbar. For the spot welded samples the number of connected laminations decreases from 3 to 2, thereby reducing the size of possible local eddy current paths. Magnetically the spot welded samples slightly improve for the welding under vacuum. Though, differences in microstructure can already be observed, the effects of solidification microstructure and HAZ grain sizes on the magnetic properties, as well as the influence on eddy current paths and mechanical stress need to be further investigated.

In Fig. 8 the influence of welding atmosphere pressure on ring core 4 is investigated in greater detail. Only a slight change of coercivity and required magnetic field strength can be observed for welded samples under vacuum and under atmospheric pressure. The two samples welded at 100 mbar and 1 mbar are almost congruent. With a rounded value of 3.1 W/kg, they have the same loss for all three hysteresis loops.

a) Welded at atmosphere pressure 50 Hz, 1.0 T



b) Welded at 1 mbar - 50 Hz,1.0 T

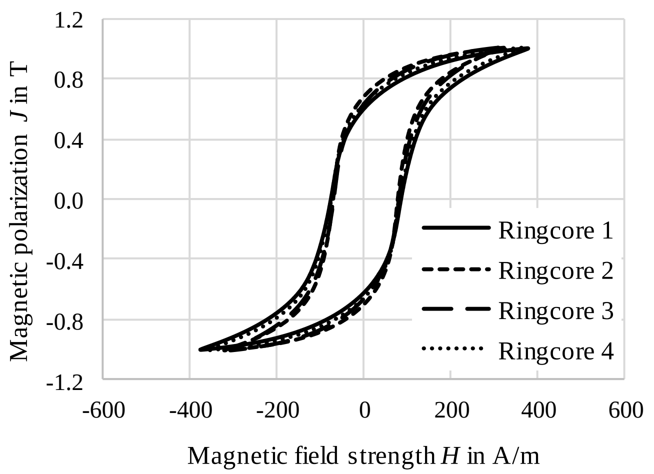


Fig. 7: *J*-*H*-hysteresis curves at 1.0 T and 50 Hz for Ring cores 1-4 with variation of welding pressure, (a) atmosphere pressure, (b) 1 mbar vacuum.

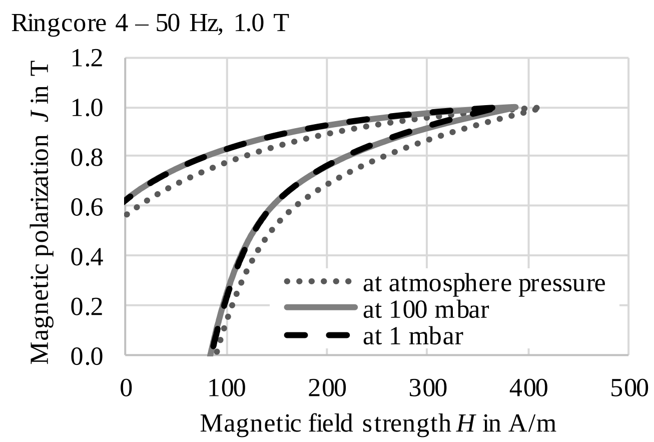


Fig. 8: Influence of welding pressure on the *J*-*H*-hysteresis curve for Ring core 4 at 50 Hz and 1.0 T.

IV. Conclusions

In this paper a novel laser welding strategy for electrical steel laminations is introduced. In opposition to commonly adapted welding techniques of perpendicular lines that connect laminations across the whole lamination stack, distributed welding spots were introduced as a method to connect laminations. The magnetic properties were characterized at different frequencies and polarization levels in order to enable a correlation to underlying, physical influences.

Mechanical stress, microstructure change and the development of short circuits due to the connection of laminations were regarded as prime sources for the deterioration of magnetic properties.

At low frequencies, ring cores with perpendicular welding lines have lower loss and better magnetization than both regarded modifications with distributed welding spots. This is connected to the mechanical residual stress state of the ring cores as a result of the thermal impact of welding. Additionally, the volume of affected microstructure is smaller for the welding lines. At increasing frequencies, the eddy current component becomes dominant and the relative loss increase becomes distinctly smaller for the spot welded samples.

The influence of atmospheric pressure on the magnetic properties is also noticeable. The detrimental effect of linear welding is increased by welding under vacuum. This is due to the increased penetration depth at consistent welding parameters. The spot welding however is less affected magnetically.

As a result it can be concluded that the presented novel welding strategy is promising. Especially as an approach for higher frequency applications. In the next step the laser parameters need to be adjusted to reduce residual stress and control microstructure change and therefore enable lower hysteresis loss and better magnetization also for low frequencies. And further the contribution of the material changes due to welding on the dynamic loss contributions need to be studied further.

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